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COMMITEE ON THE PEACEFUL USES
OF OUTER SPACE

UPPER ATMOSPHERE STUDIES FOR WEATHER AND ENVIRONMENT MONITORING

Note by the Secretariat

1. The Working Group of the Whole to Evaluate the Implementation of the Recommendations of the Second United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE 82), in the report on the work of its fourth session, made a series of recommendations concerning the preparation of reports and studies by the Secretariat and the compilation of information from Member States (A/AC.105/456, annex II, paras. 4, 5 and 6).

2. The Working Group recommended, in paragraph 5 (b) of its report, that a few specific studies should be carried out to demonstrate the potentials of space technology, including a study on upper atmosphere studies for weather and environment monitoring. The Working Group recommended that, as a first step, information on some of the subjects might be provided as part of the United Nations efforts in conjunction with International Space Year (ISY).

3. The report of the Working Group was adopted by the Scientific and Technical Sub-Committee at its twenty-seventh session (A/AC.105/456, para. 21) and the recommendations were endorsed by the Committee on the Peaceful Uses of Outer Space at its thirty-third session 1/ and by the General Assembly in its resolution 45/72 of 11 December 1990.

4. The present study was prepared using a variety of national and international sources, including previous United Nations studies on related topics. Those sources are listed in the references at the end of the study.

5. The purpose of the study is to provide information on developments in upper atmospheric studies, particularly those developments involving space observations, and on the relation of upper atmospheric processes to weather, climate and the environment. The study emphasizes the importance and the complexity of the problems that upper atmospheric science is addressing. It is impossible, of

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course, to cover all aspects of upper atmospheric science in detail, and the many existing and planned atmospheric research projects are not described, since they evolve rapidly and would require lengthy technical descriptions. Emphasis is given to the evaluation of new knowledge of the upper atmosphere, the most important problems that remain to be solved and the space technology that is available for solving those problems.

6. The term "upper atmosphere" is used in the study to designate the atmosphere above the troposphere that is bound to the Earth by its gravitational and magnetic fields and contains a wide variety of particles, electromagnetic fields and waves.

7. The summary of the study, which appears immediately below, has been translated into all the official languages of the United Nations. The full study, which is contained in the annex to the present report, is being distributed only in the language in which it was prepared because of its technical character.

SUMMARY OF THE STUDY

8. Experiments using satellites and rockets have greatly expanded our knowledge of the upper atmosphere, well beyond the regions previously explored, providing information on such phenomena as the distribution of various molecules, atoms and ions as a function of altitude and latitude, and of their daily, seasonal and longer-term variations. These experiments, however, have revealed that upper atmospheric phenomena are much more complex than previously expected, and many features, including fundamental ones, are still not adequately understood after more than 30 years of research. Predictions of the density of the upper atmosphere based on current models, for example, are often inaccurate by as much as 15 per cent.

9. There is still little understandiing of the short-term effects of solar and upper-atmosphere variability on the lower atmosphere and the biosphere. It is known, however, that the upper atmosphere is a dynamically active "input processing" region, in which variable flows of energy and matter from outer space, as well as from the Earth below, lead to changes whose effects, in turn, propagate downward to lower altitudes, sideways to other latitudes and longitudes and upwards into space.

10. Most of the effects of upper atmospheric processes on weather, climate and the biosphere are subtle, and their study poses a great challenge to scientists. In evaluating the importance of these effects, it must be recognized that the global atmosphere-biosphere system is characterized by a variety of complex responses and instabilities and by a vast inventory of free energy that can be released to cause substantial change through triggering processes initiated by small initial perturbations.

11. Like other parts of the Earth's environment, the upper atmosphere is subject to pollution by human activities. Industrial effluents transported upward into the stratosphere, orbiting debris, electromagnetic waves emitted by electric power grids and high-power transmitters, and jet and rocket engine exhaust are all

examples of known "pollutants". Some of them pose a potential threat to the long-term integrity of the upper atmosphere and its protective ozone layer, and to spacecraft and human activities in orbit around the Earth.

12. The so-called greenhouse gases, primarily water vapour and carbon dioxide, play a vital role in regulating the temperature of the Earth and its atmosphere. In the absence of these gases, the average surface temperature would be 33° C colder than it is, and the Earth would be a frozen, lifeless planet. The natural greenhouse effect of the atmosphere is an essential component of the regulating mechanism that has maintained the Earth's climate within a range suitable for the development of life over the course of four billion years. There is now, however, growing concern that global surface temperatures will rise further due to steadily increasing concentrations of the various greenhouse gases and will disrupt existing ecological balances.

13. The Scientific Committee on Solar-Terrestrial Physics of the International Council of Scientific Unions (ICSU) has prepared, for the period 1990-1995, a Solar-Terrestrial Energy Programme (STEP), which will study the solar-terrestrial environment as a complex interactive system whose overall behaviour often substantially departs from a simple combination of its components. Several broad questions will be addressed by the project; they are also of relevance to the subject of the present study:

(a) What are the long-term and short-term changes in solar electromagnetic and corpuscular energy inputs, and what are the processes responsible for solar variability?

(b) What are the effects of variable inputs from the Sun, from outer space and from the Earth below on the upper atmosphere, and what are the processes responsible for its response and feedback?

(c) What is the role of the stratosphere and mesosphere in processing source gases of tropospheric origin, and in what ways do natural effects, such as solar variability and volcanism, mask changes of anthropogenic origin?

(d) What are the processes that couple the upper atmosphere to the lower atmosphere, and what are the effects of this coupling on weather, climate and the biosphere?

14. To study these problems, a set of research projects is being prepared through the co-operation of several ICSU bodies, including the Committee on Space Research (COSPAR), the Scientific Committee on Solar-Terrestrial Physics and the International Astronomical Union. The ultimate practical goal will be to improve our ability to predict the effects of variable inputs of solar energy and disturbances on the terrestrial environment and on human systems in space and on Earth. The programmes will involve ground-based, aircraft, balloon, rocket and satellite experiments, theoretical analysis and simulation studies, as well as data processing and information systems. Crucial to the success of these projects are the solar-terrestrial spacecraft missions recommended by the Inter-Agency Consultative Group (IACG) as the next co-operative projects of the United States of America, the European Space Agency, Japan and, possibly, Intercosmos.

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15. Human activity continues to expand outwards. Today, satellite systems for communications, weather prediction, navigation and remote sensing of natural resources are providing essential support for many social and economic activities. The need to predict the "weather and climate" in space is becoming as important as the need to predict weather and climate in the inhospitable regions on Earth into which human activity has moved during the last few decades, including the Arctic, low-lying coastal areas and arid lands. These expanding human activities only underscore the importance of upper atmospheric research.

Notes

1/ Official Records of the General Assembly, Forty-fifth Session, Supplement No. 20 (A/45/20), para. 30.

Annex

UPPER ATMOSPHERE STUDIES FOR WEATHER AND ENVIRONMENT MONITORING

Study by the Secretariat

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INTRODUCTION

1. The Earth's atmosphere is part of a complex solar-terrestrial system in which all human activities take place. Not only does the atmosphere support life, providing oxygen and carbon dioxide that living things need for their metabolic processes, but it also protects life from many hazards of extraterrestrial origin. The atmosphere screens the Earth's surface from meteorites, from X-rays and gamma rays and from many high-energy atomic and subatomic particles.

2. As a result of sounding rocket and satellite measurements, an understanding of the enormous complexity of the Earth's atmosphere and its many layers has begun to develop. In addition, however, over the past few years important new questions have arisen concerning the upper atmosphere and the possible serious consequences of human activities. An increased understanding of the upper atmosphere and its relation to the lower atmosphere is necessary in order to ensure that we do not do irreversible damage to our atmosphere.

3. The present study was prepared using a variety of national and international sources, including previous United Nations studies on related topics. These sources are listed in the references at the end of the study.

4. The purpose of the study is to provide information on developments in upper atmospheric studies, particularly those developments involving space observations, and on the relation of upper atmospheric processes to weather, climate and the environment. The study emphasizes the importance and the complexity of the problems that upper atmospheric science is addressing. It is impossible, of course, to cover all aspects of upper atmospheric science in detail, and many existing and planned atmospheric research projects are not described, since they evolve rapidly and would require lengthy technical descriptions. Emphasis is given to the evaluation of new knowledge of the upper atmosphere, the most important problems that remain to be solved and the space technology that is available for solving those problems.

5. The term "upper atmosphere" is used in the study to designate the atmosphere above the troposphere that is bound to the Earth by its gravitational and magnetic fields and contains a wide variety of particles, electromagnetic fields and waves. While the troposphere, in which our weather takes place and on which life depends, is the part of the atmosphere of the most obvious importance, the upper atmosphere is also vital to life on Earth, both through its direct effects on the surface environment and through its effects on the troposphere.

I. THE UPPER ATMOSPHERE

A. Regions of the upper atmosphere

6. A planetary atmosphere is a gaseous envelope bound to the planet by its gravitational field and continually decreasing in density with altitude above the surface. The height at which the Earth's atmosphere finally merges into interplanetary space varies in time and with latitude and is not easily defined. At about 600 km, however, the density of the atmosphere is so low that it no longer behaves as a gas in the classical sense of molecules continually colliding and rebounding from each other. Instead, each molecule travels a long distance before encountering another molecule or atom.

7. In studying the atmosphere, scientists have identified a number of atmospheric layers, called "regions" or "spheres", with different characteristics (see fig. 1). The density of the atmosphere and its other characteristics actually change gradually with height, and the different regions slowly merge into one another without distinct boundaries. Despite the artificiality of the "regions" and "boundaries", these concepts are essential for the study and discussion of the upper atmosphere.

8. The lower atmosphere is called the troposphere (from the Greek word tropos - to turn) and is the region where the heating of the surface by solar radiation and the evaporation and condensation of water produce the turbulent conditions that we call weather. The major cloud systems are confined to this region, which is therefore the domain of meteorologists. The temperature in the troposphere decreases steadily with altitude; at its top, which is called the tropopause, the typical temperature is -50° C, and winds exceeding 160 km per hour are common.

9. The stratosphere (from the Latin stratum - layer) extends from the tropopause (at about 15 km altitude in the tropics and 10 km near the poles) to the stratopause at about 50 km, where the atmospheric temperature reaches -20° C to +20° C. Within the stratosphere, scientists sometimes distinguish a sub-region, the ozonosphere, at an altitude of around 25 km, at which solar ultraviolet radiation (with wavelengths of 250-310 nanometres) is absorbed, dissociating molecular oxygen into atomic oxygen, which later recombines with molecular oxygen to produce ozone. This ultraviolet absorption is the main cause of the increase of temperature with height in the stratosphere.

10. The mesosphere (from the Greek mesos - middle) extends from the stratopause to the mesopause at about 80 km above the Earth's surface. This region is characterized by a decline in temperature with increasing altitude to a second minimum at the mesopause (about -120° C in summer and -50° C in winter). This temperature distribution is probably due to circulation effects, as there is little absorption of solar radiation at this level. The stratosphere and mesosphere are sometimes jointly referred to as the middle atmosphere, with the term upper atmosphere reserved for higher regions only.

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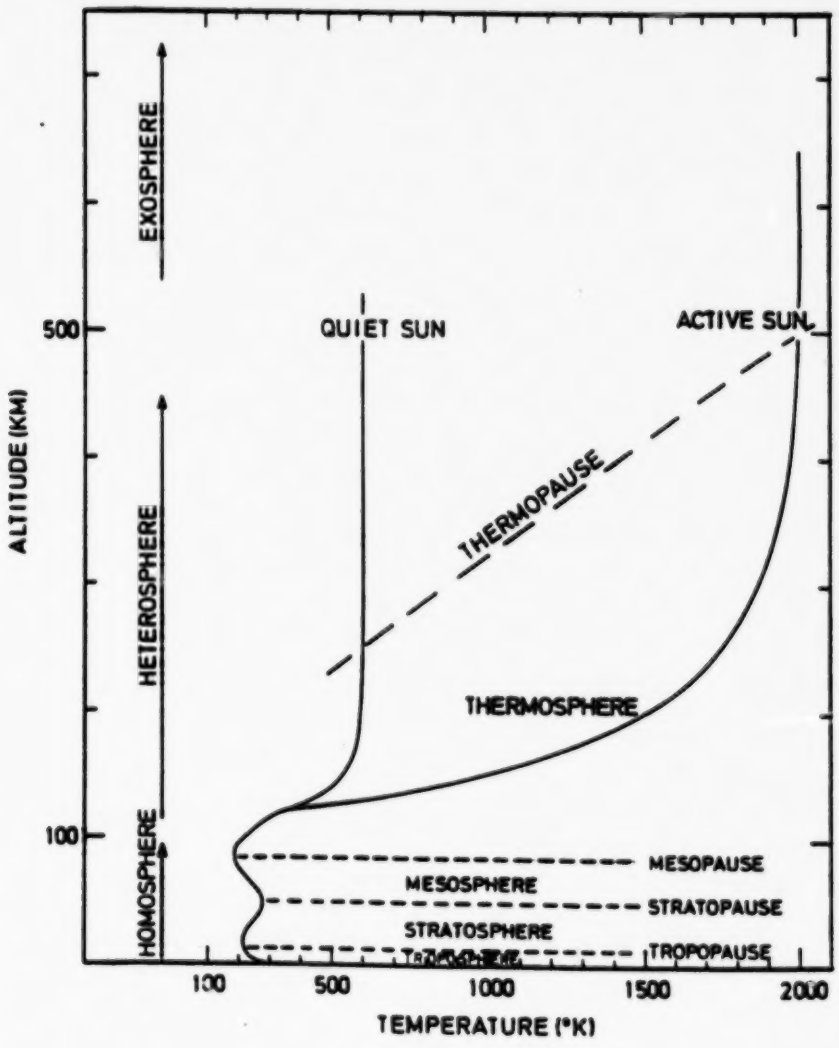

Figure 1. Vertical distribution of temperature in the atmosphere (NASA).

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11. The thermosphere (from the Greek therme, meaning heat) is the highest part of the atmosphere distinguished by its thermal properties, and represents the transition from the Earth-bound atmosphere to interplanetary space. The temperature in the thermosphere increases with altitude, due to absorption of solar ultraviolet energy, and varies with the level of solar activity. The top of the thermosphere, called the thermopause, varies in altitude and in temperature, depending on solar activity. The altitude of the thermopause varies between 200 km and 500 km and the temperature can reach 400° C to 2000° C.

12. The upper part of the thermosphere, above 300 km, is sometimes called the exosphere and is so tenuous that atoms or molecules can travel many kilometers before colliding with others (i.e., their mean free path becomes very large). Some of them, through their thermal kinetic energy, are even able to escape from the gravitational field of the Earth and become part of the interplanetary medium. The exospheric temperature above the thermopause depends only on solar activity, not on altitude (see fig. 1).

13. The situation in the thermosphere is complicated by the fact that some of the particles are electrically charged (ionized). These ionized particles, although physically mixed together with uncharged particles, are thought of as forming an "independent" region called the ionosphere. Interactions between ionospheric particles and solar electromagnetic and corpuscular radiation produce a variety of phenomena ranging from auroras to effects on radiocommunications.

14. An important conclusion of upper atmospheric research is that the atmospheric regions cannot be studied independently of each other because they interact in many ways.

B. Composition of the neutral upper atmosphere

15. From a scientific point of view, the Earth's atmosphere may be considered as a perfect gas composed of atoms and molecules, of which only a small proportion are charged and therefore influenced by the geomagnetic field. The primary properties of the neutral (non-ionized) atmosphere are its density, temperature, composition and motion. The mixing and the movement of the atmosphere and the chemical reactions that take place within it are important processes that affect the distribution of the neutral particles. One such important process is the dissociation, by solar ultraviolet radiation, of molecular oxygen and nitrogen into atoms, which may then diffuse to higher or lower altitudes, or may recombine by chemical processes.

16. The density, temperature and pressure of the neutral atmosphere are related by the ideal gas law, which states that the pressure is proportional to density and temperature. A second important physical principle, the hydrostatic equation, states that the rate at which pressure decreases with altitude is proportional to the density of the atmosphere. In the lower atmosphere, the pressure decreases by a factor of about 3 every 10 km, a distance called the scale height.

17. Where no mixing occurs, the vertical distribution of atmospheric gases is determined by gravity, and each gas has its own scale height, determined by the mass of a molecule or atom of the gas. The concentrations of heavy gases such as molecular nitrogen and oxygen then decrease more rapidly with altitude than the concentrations of lighter gases such as hydrogen, helium or atomic oxygen or nitrogen, and hence the relative concentrations change with altitude. Observation of meteor trails and analysis of samples of air collected by sounding rockets has established that mixing does not occur above about 110 km, called the turbopause.

18. The part of the atmosphere which is thoroughly mixed (below 110 km) is often called the homosphere, while the non-homogenous upper part is known as the heterosphere. At the base of the heterosphere, concentrations of atomic oxygen, molecular oxygen and molecular nitrogen are roughly equal (about 10^{10} to 10^{11} particles per cubic centimeter), while the concentration of atomic nitrogen is only a few per cent of the atomic oxygen concentration, since there is little photodissociation of nitrogen molecules. Furthermore, the nitrogen atoms react with molecular oxygen to form nitric oxide, which then reacts further with nitrogen atoms, resulting in their mutual destruction, with atomic oxygen and molecular nitrogen as products.

19. In the heterosphere, the concentration of molecular nitrogen decreases by about one third every 25 km, whereas the concentration of atomic oxygen decreases by the same amount every 50 km. Above about 300 km, atomic oxygen becomes the major component of the neutral atmosphere and remains so until about 1,000 km, at which altitude hydrogen and helium begin to predominate.

20. The total mass of the atmosphere, which can be computed from the surface pressure, the force of gravity and the surface area of the Earth, amounts to 5×10^{18} kg. Because of the exponentially decreasing pressure, more than 90 per cent of this mass resides in the troposphere, and less than 1 per cent above the stratosphere. The lack of mass, however, does not mean that processes in the upper levels of the atmosphere are not important. The upper atmosphere is a dynamically active "input processing region" in which energy and mass received from space cause major changes whose effects propagate to lower regions.

C. The ionosphere

21. Before space technology was available, the only information on the ionosphere came from ground-based radio sounding (called ionosondes) of the atmosphere using a range of radio frequencies penetrating to different layers of ionization. Those experiments provided information only on concentrations of electrons at heights below the maximum density of the ionosphere. The measurements revealed three fairly well-defined layers of ionization in the 80 to 400 km interval (see fig. 2). These layers were designated the D-, E- and F-regions, in ascending order. Even though the ionosphere is often characterized in terms of its electron density peaks, it must be remembered that it is the concentration of specific ions and their reactions which determine the behaviour of the ionosphere as a whole as well as the different ionospheric regions.

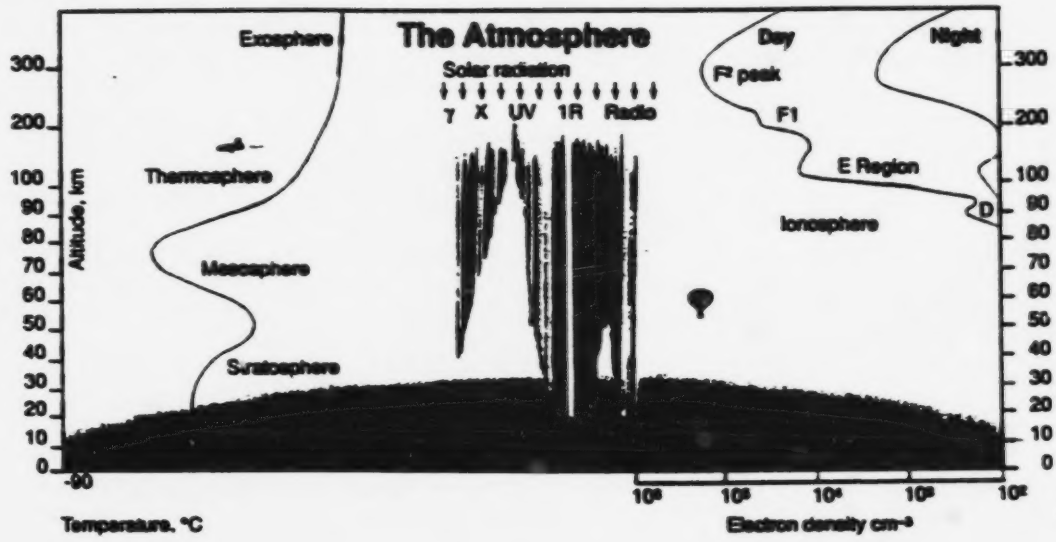

Figure 2. The atmospheric parameters as a function of altitude: the temperature of neutral atmosphere (left), absorption of different radiation (centre) and electron density in the ionosphere (right). According to NASA.

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22. In the early models of the ionosphere, theorists realized that different species of ions produced by ionizing solar radiation might be responsible for the occurrence of different layers in the ionosphere. The layers are caused, initially, by photo-ionization of the different atmospheric constituents, in particular molecular nitrogen, molecular oxygen and atomic oxygen. A full understanding of the composition, however, must take into account various reactions which occur among the ions and electrons and the neutral atmospheric constituents.

23. In the lowermost regions, molecular ions predominate, while in the upper part of the F-region (the F_2 region), ions of atomic oxygen become most important. Above the F_2 peak, occurring at an altitude of about 300 km, the plasma (i.e., a mixture of ions and electrons) also contains significant proportions of hydrogen and helium ions. Electron and ion temperatures at these altitudes are higher than the neutral exospheric temperature and reach several thousand degrees Celsius. Below 1000 km, the plasma densities are several orders of magnitude smaller than the neutral density, whereas in the magnetosphere the ionized component predominates.

24. The concentration of ions is quite variable, due primarily to the day-night illumination cycle. At night, the D- and E-regions practically disappear (see fig. 3), but the upper F-region survives, because the lifetime of ions at that altitude is longer than half a day. These ionospheric layers are very important for communications, since all non-satellite long-distance radio communication uses reflections of radio signals from the ionosphere. Since the D-region also absorbs radio signals, it greatly limits long-distance communications during the day, but not at night. The much higher frequencies used for television and FM (frequency-modulated) radio transmissions are normally not affected by the ionosphere and are therefore limited to nearly line-of-sight propagation. Photo-ionization, and hence radio reflections from the ionosphere, also varies with the solar cycle.

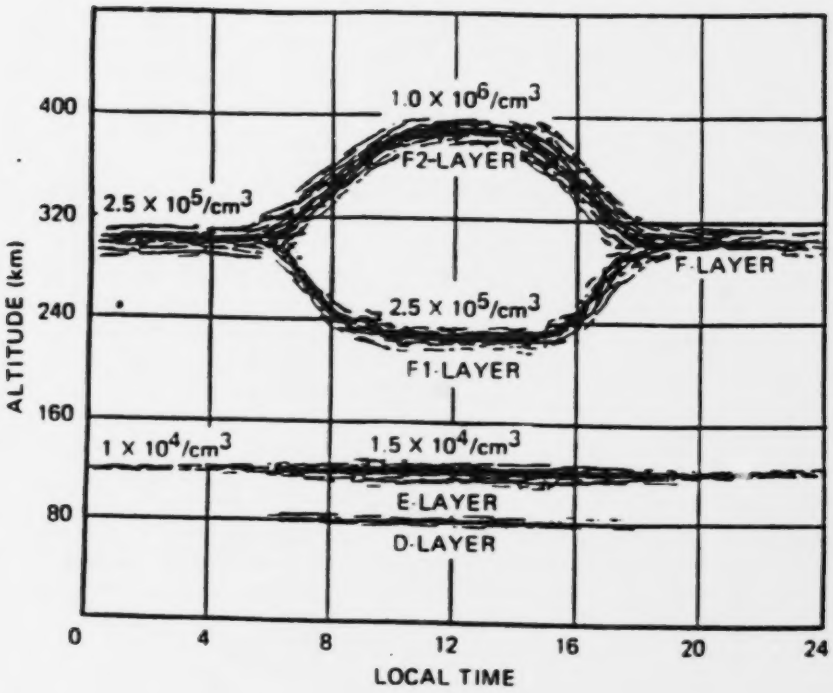

Figure 3. The electron densities as a function of altitude and local solar time (NASA).

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D. The magnetosphere and plasmasphere

25. The magnetosphere is that region of the upper atmosphere in which the movement of ionized plasma is determined primarily by the geomagnetic field. It extends upwards from about 150 km, the lower F (F_1) region of the ionosphere, below which the movement of ions is determined primarily by collisions with neutral particles (for electrons, collisions are dominant below about 90 km). The outer limit of the magnetosphere is determined by the interaction of the geomagnetic field with the solar wind. On the day side of the Earth, the geomagnetic field is compressed by and deflects the solar wind at a distance of about 10 Earth radii (about 64,000 km), while on the night side the magnetosphere extends as a long tail to very large distances (see fig. 4).

26. There are several regions of the magnetosphere where the behaviour of thermal plasma (mainly ionized hydrogen and helium) is determined by different effects. At low geomagnetic latitudes, the plasmasphere is a region of relatively high ion density contained along the closed lines of geomagnetic force. The radiation belts discovered during the earliest space activities are part of the plasmasphere, as are various electric currents connected through the ionosphere. The low-energy (several electron volts (eV)) particles in the plasmasphere are mostly electrons and ions of ionospheric origin, while the high energy (keV to MeV) particles are trapped particles from outer space.

27. The upper boundary of the plasmasphere is the plasmapause, a rather uneven surface shaped like an asymmetrical torus. At higher latitudes, the field lines of the magnetosphere on the day side are swept back over the pole into the tail where they eventually join. The steady flow of energetic particles from the Sun - the solar wind - does not reach the upper atmosphere directly. Rather, it is deflected by the magnetosphere, which is thereby deformed into an extremely complex system. The transfer of solar wind energy into the magnetosphere determines the extent to which processes within the magnetosphere perturb the lower ionosphere and plasmasphere.

28. Most of the disturbances of the ionosphere and plasmasphere as a result of the solar wind occur in the polar upper atmosphere, in the regions called the polar cusps. Auroras and other airglow phenomena in these regions result from the interaction of energetic particles trapped in the radiation belts with the neutral atmosphere. This is the reason why investigations of auroras and related effects are so important for the understanding of atmospheric physics.

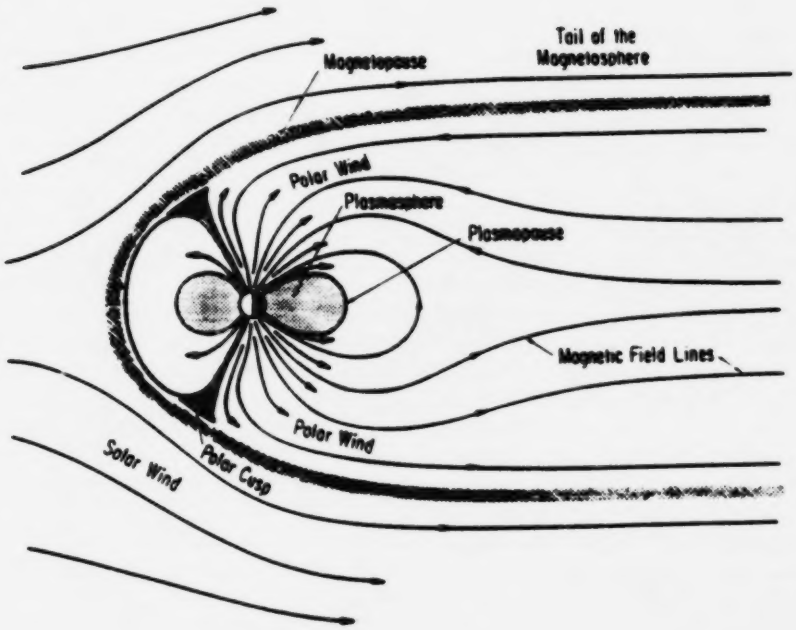

Figure 4. Schematic view of the Earth's plasma environment (NASA).

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II. SPACE TECHNOLOGY AND UPPER ATMOSPHERE STUDIES

A. Density of the upper atmosphere

29. Immediately after the launch of the first artificial satellites during International Geophysical Year, it was discovered that their orbits decayed more rapidly than had been expected. The natural explanation was that the Earth's upper atmosphere was more extensive and denser at high altitudes than scientists had believed on the basis of earlier balloon and sounding-rocket measurements. Another surprise was the discovery of large changes in atmospheric density at satellite altitudes as a function of solar activity.

30. The atmospheric drag experienced by a satellite depends on the characteristics of the satellite and of the atmosphere. As an approximation, the atmospheric drag is proportional to the square of the satellite's velocity, to its cross-sectional area divided by its mass and to the atmospheric density. The orbits of large, light satellites therefore decay more rapidly than small dense satellites. The rate of orbital decay also depends upon the molecular flow around its surface, which depends on the shape of the satellite and is described by the "drag coefficient". The most reliable determinations of upper atmospheric density come from observations of spherical satellites, since they have a fixed area-to-mass ratio. A series of high-drag satellites, mainly large balloons, was used to accurately determine spatial and temporal variations of atmospheric density.

31. Because of the almost exponential decrease in atmospheric density with altitude, most orbital drag occurs at the lowest point of the orbit (perigee). This has the effect of gradually decreasing the highest point of the orbit (apogee), keeping the perigee at nearly the same altitude until the orbit is almost circular. Various formulas have been developed for calculating the atmospheric density near perigee on the basis of observations of changes in orbital period. Usually, several orbital revolutions of the satellite are needed to determine the period and the rate of its change. The densities determined by this method are therefore average values in which time variations more rapid than the orbital period are averaged out.

32. Since the position of perigee relative to the Earth's surface is continually changing, primarily due to the polar flattening of the Earth, the density of the upper atmosphere over different parts of the Earth can be measured using orbital observations of a single satellite. However, the development of a model that takes account of the complexity of the density distribution in the upper atmosphere requires observations of many satellites. Unfortunately, this method does not allow for direct measurement of individual components of the atmosphere, since only total density is obtained. Nevertheless, the variations in the density of the upper atmosphere were discovered this way and are continually being monitored.

33. The atmospheric drag experienced by a satellite can also be measured directly on board the satellite. The instrument used for the purpose, called an accelerometer, consists of a suspended mass together with sensitive measuring devices to monitor the displacements of the mass. The accelerometer is located near the centre of the satellite, where it is not directly affected by surface

forces such as atmospheric pressure or solar or terrestrial radiation. These drag forces act on the outer framework of the satellite, and hence the displacement of the accelerometer mass relative to the framework is a measure of the deceleration due to atmospheric drag.

34. The accelerometer technique for measuring atmospheric density allows more localized measurements than orbital decay observations, which integrate drag over several orbits. The technique has been used on a number of satellites, including a series of five Italian San Marco satellites launched since 1964. The most sensitive accelerometer to date was carried on the French Castor satellite from 1975 to 1979. Three Atmospheric Explorer satellites of the United States of America launched in 1973 and 1975 also used the technique to measure atmospheric density at altitudes as low as 130 km, using a special propulsion system to maintain the satellite in orbit at such low altitudes. Since the accelerometer technique provides very good temporal and spatial resolution, it is valuable for detailed investigation of density variations at low altitudes.

35. While many characteristics of the atmosphere, including density, temperature and composition, can be measured directly by instruments on satellites, and have been measured by a number of satellites since the beginning of the space age, satellites have provided only a limited series of isolated measurements. Taking into account the complexity and great variability of the upper atmosphere, the number of satellite observations has not been sufficient.

36. Recently, more emphasis has been placed on the monitoring of trace constituents of the atmosphere, especially by remote sensing methods such as spectrometry and photometry. The Upper Atmosphere Research Satellite (UARS), to be launched by the United States at the end of 1991, will provide the first global measurements of the chemistry, dynamics and energetics of the upper atmosphere during its planned three-year lifetime. The United States is also co-operating with Italy in planning three experimental missions, starting in 1991, using a tethered satellite system (TSS), consisting of a sub-satellite to be deployed downward from the shuttle orbiter on a cable almost 100 km long. This will make possible direct upper atmospheric measurements in the region between the maximum altitude of aircraft and balloons and the minimum altitudes of satellites.

B. Variations in upper atmospheric density

37. Within the variations in upper atmosphere density, five main components have been identified: a diurnal variation; a variation with an average period of 27 days; a semi-annual variation; a long-term variation associated with the 11-year solar cycle; and variations correlated with geomagnetic activity.

38. The diurnal variation is the largest variation and is due to the daytime heating and nighttime cooling of the upper atmosphere. Drag studies have shown that, for all altitudes above 200 km, the atmospheric density has a sharp maximum at 1400 hours local solar time (LST) and a shallow minimum at about 0400 hours LST, indicating that an "atmospheric bulge" is formed during the daytime with its maximum extension delayed two hours after local noon. The amplitude of this effect

increases rapidly with altitude, from almost no change at 120 km, to less than 10 per cent diurnal variation at 200 km, to daytime densities up to eight times higher than nighttime values at 600 km (see fig. 5).

39. The variations in drag with a period of 27 days were identified by observations of a number of early satellites (see fig. 6). A strong correlation exists between these observations and the intensity of solar radio emissions at 10.7 cm wavelength. This radiation does not itself heat the upper atmosphere, but it can be easily monitored on the ground and serves as an indicator of solar extreme ultraviolet radiation. The period of 27 days corresponds to the rotation period of the Sun, indicating that the atmospheric density fluctuations are caused by radiation emitted from active regions on the solar surface that pass across the visible face of the Sun every 27 days. This effect, due to the rotation of the Sun, is not as regular as the diurnal effect due to the rotation of the Earth.

40. The main characteristics of the semi-annual variation, which is observed in the altitude range from 200 to 1,000 km, are a pronounced minimum in June-July and a second small minimum in January. The maxima occur in September-October and in March-April, with the former usually somewhat larger than the latter. While it seems clear that these variations are due to the tilt in the Earth's axis relative to its orbit around the Sun and to the resulting apparent seasonal movement of the Sun north and south of the equator, there is still no general agreement on the precise explanation of this variation.

41. Data on upper atmospheric density are now available for several 11-year cycles of solar activity (see fig. 7). These data reveal that atmospheric density at altitudes of several hundred kilometres changes by a factor of 10 to 50 in response to high-energy radiation from the Sun.

42. In addition to the variations produced by the changing solar extreme ultraviolet radiation, there are also variations that are correlated with geomagnetic variations. During geomagnetic storms, atmosphere density at high altitudes may increase briefly by an order of magnitude, usually with a time delay of about five hours between the start of the magnetic storm and the temperature rise and density decline in the exosphere. Such fluctuations due to geomagnetic storms are difficult to predict and are consequently responsible for much of the uncertainty in the predictions of satellite motion and lifetimes, particularly during the final phases of their existence.

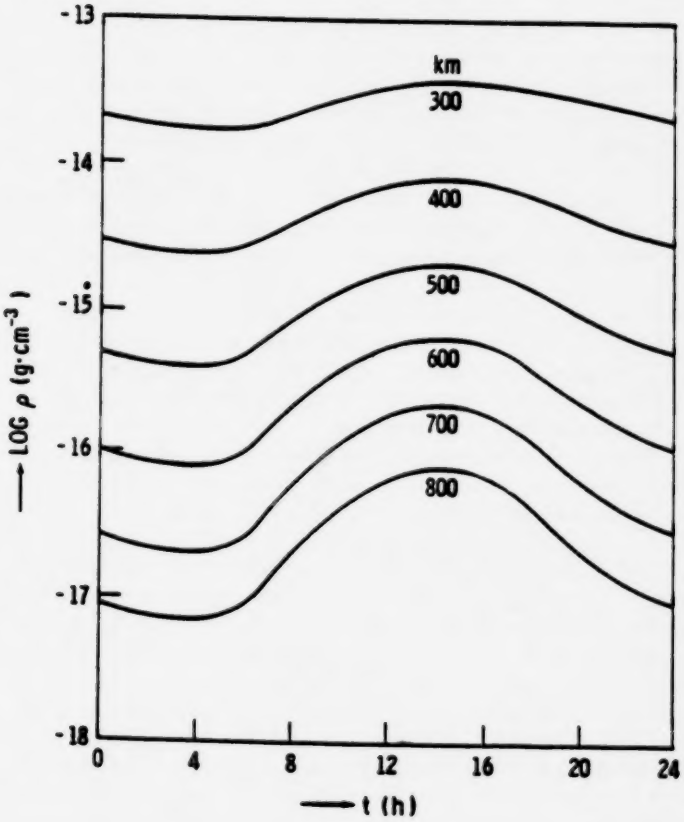

Figure 5. The diurnal variation of the upper atmospheric density for various altitudes for a medium solar activity. According to the COSPAR International Reference Atmosphere, 1964.

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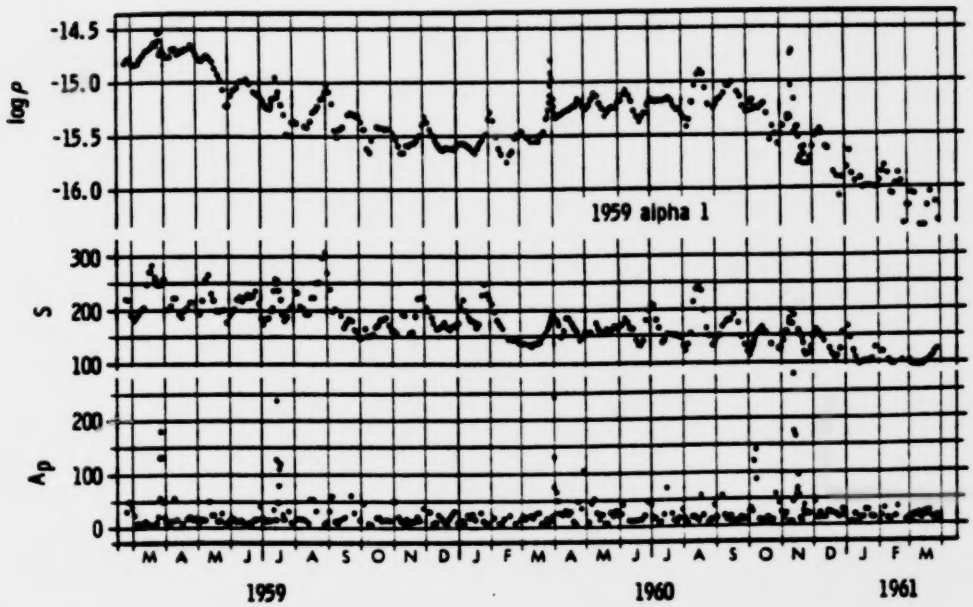

Figure 6. A comparison of the variations of exospheric density from satellite 1959 alpha 1 and solar activity, showing the 27-day periodicity. Energy S is measured in units of 10^{-22} watts/m^2. From M. Roemer, Report Number 68 of the Astronomical Observatory of Bonn University.

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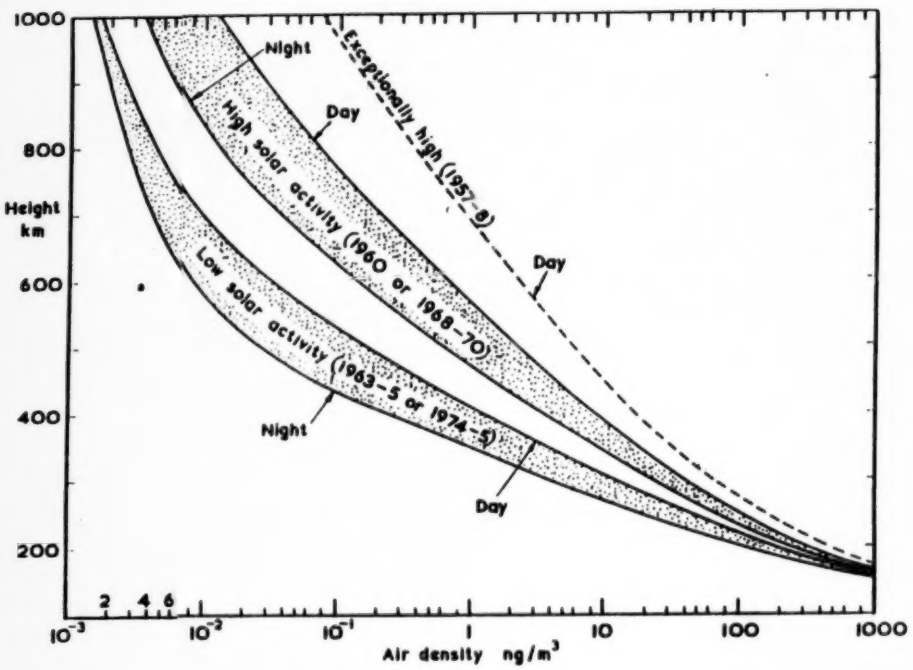

Figure 7. **Variation of air density with height from 150 to 1,000 km for high and low solar activity. According to the COSPAR International Reference Atmosphere 1972.**

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C. Atmospheric models

43. From the wealth of satellite drag data and from direct measurements of atmospheric properties, a clearer picture of the behaviour of the atmosphere is now available. Nevertheless, since most measurements are still isolated in space and time, models of the atmosphere are required to correlate and compare the data. Because of the large and rapid variations, any model which yields only average values cannot fulfil the requirements for a useful reference model.

44. In recent years, several empirical models have been constructed which describe the temporal and spatial changes of the thermospheric temperature and density under different geophysical conditions. They are indispensable for satellite orbital predictions, including the computation of satellite lifetimes and the prediction of space debris re-entry. Important as they are, these models are far from perfect, and those who use them need to be aware of their limitations. First, the database used for their construction is not homogeneous and may contain systematic errors. Secondly, the algorithms chosen may not fully reflect the physics of the processes to be modelled and usually do not reproduce small-scale variations. It is therefore important to keep in mind the above limitations in estimating the accuracy of the models. One way of estimating the uncertainty in the predictions is to compare the predictions of the different models. However, such analysis is valid only when both models are equally appropriate for the conditions in question.

45. Even the most sophisticated models, such as MSIS-83 (Hedin et al., 1983), C (Kohnlein, 1980), DTM (Barlier et al., 1978) or J-77 (Jacchia, 1977) show differences of up to 33 per cent in the predicted densities. Differences of 30 to 55 per cent were observed between the ESRO 4 model (von Zahn et al., 1977) and observed densities of atmospheric components during geomagnetically quiet intervals. It is now generally accepted, based on comparisons of model predictions with observations, that the average standard deviation of the difference between measured densities and model densities is about 15 per cent. Substantial improvement is therefore needed for accurate modelling of orbital behaviour and atmospheric re-entry of satellites and orbital debris.

46. A continuing effort is being made by COSPAR Sub-Commission C.4 on the COSPAR International Reference Atmosphere (CIRA) to improve its reference models. The new CIRA:1986 reference model is a successor to models adopted by COSPAR in 1961, 1965 and 1972 and is divided into two parts, the thermosphere and the middle atmosphere. The new middle atmosphere model includes satellite data whereas the previous version used only in situ and ground-based measurements. The two hemispheres are treated separately and more detailed data, including variations such as planetary waves, are included for the stratosphere and mesosphere. Included for the first time are systematic variations of ozone with latitude and season in both the stratosphere and the mesosphere, derived from data from six satellites. The International Reference Ionosphere 1990 Handbook is being prepared by the National Space Science Data Center and World Data Center A under the auspices of the International Union of Radio Science (URSI) and COSPAR.

D. Geomagnetic activity

47. Geomagnetic activity is caused by streams of energetic particles emitted from the active regions on the Sun, including sunspots and flares, which under "favourable" geometric conditions can reach the Earth and have considerable effects in the plasmasphere and ionosphere. Geomagnetic storms are violent fluctuations in the geomagnetic field over a period of one to several days, whereas geomagnetic "substorms" are those perturbations which occur over a few hours and are more localized in polar latitudes. Both geomagnetic storms and substorms are associated with magnetospheric disturbances, visual auroras and radio-wave absorption.

48. As geomagnetic activity is correlated with solar disturbances, geomagnetic data are often used as an indirect indicator of solar activity. A variety of indices have been used, but in recent studies the "planetary indices" K_p and A_p are most common. At a geomagnetic observatory, a local index K, ranging from 0 for the quietest conditions to 9 for the greatest disturbances, is determined for each three-hourly interval. The index is based on the largest fluctuations of the three components of the geomagnetic field strength. Local influences are eliminated by combining indices from 12 stations near the auroral zone, giving an average index K_p called the planetary three-hourly index. The daily index A_p is then mathematically derived from the eight three-hourly K_p values. Tabulations of K_p date from 1932.

49. The effects of solar activity were evident during the year 1989, which was punctuated with powerful geomagnetic storms that disrupted the Earth's ground and space electromagnetic environments. Several large solar storms of one to two weeks' duration occurred at times when large flares erupted in rapid daily succession. One episode of solar flaring in mid-March caused auroral displays that were witnessed from record low latitudes, and high-energy solar cosmic rays were recorded world wide from July through October. Streams of high-energy protons from flare regions in August were the strongest since 1972. During one week in October, the total flux of protons with energies greater than 10 million eV exceeded the total for the entire previous 11-year solar cycle.

50. During the great geomagnetic storms in 1989, the magnetopause was compressed inward from about 64,000 km to below 36,000 km, the altitude at which geostationary satellites orbit. The intense radiation caused solar panels on geostationary and deep-space spacecraft to deteriorate markedly; some effectively aged five years in only seven days and some essential micro-electronic circuits on communications satellites failed. Magnetically oriented geostationary satellites had to rely on frequent, fuel-consuming ground-controlled actions to maintain positions, and some low-altitude satellites in near polar orbits tumbled out of control.

51. The increased atmospheric drag due to the geomagnetic storms also caused satellites and space debris to decay more rapidly. On the one hand, the rapid decay had a cleaning effect on the space environment; on the other, it complicated the tracking of such objects, and about 10 per cent of the objects normally tracked were temporarily lost. Astronauts on the Space Shuttle Atlantis during its October 1989 flight were frequently troubled by energetic protons causing flashes in their eyes. It is estimated that astronauts in deep-space spacecraft and

performing extravehicular manoeuvres outside the magnetosphere at that time would have received fatal doses of radiation.

52. During this solar activity maximum, large power-distribution systems in Scandinavia and Canada were strongly affected. The Province of Quebec was blacked out for over nine hours and some 6 million customers were left without electricity. Many failures also occurred in the United States, including the loss of two large transformers. Ship and aircraft radio navigation systems failed and high-frequency radio communications links were unusable world wide.

53. While the effects of geomagnetic disturbances on the ionosphere and the resulting perturbations of radio communications have been studied for many years, many difficult scientific problems remain, such as the formation of ionospheric irregularities and their effects on the gigahertz radio-frequency band used in satellite telecommunication and data transmission systems.

54. While satellites are ideal for observing the distribution of auroral activity around the "auroral oval" about the magnetic north pole, the limited number of satellites available for other upper atmosphere studies do not provide sufficient data for accurate study of the global and long-term effects of magnetospheric events on the lower atmosphere and on human activities. There is a need for further development and instrumentation of ground networks to provide continuous and long-term measurements of crucial magnetospheric properties and processes on a global scale.

E. Aurora and airglow

55. Auroras have been observed from the ground for a long time, but such observations of auroras are limited to the northern and southern polar regions and to periods of darkness. Nevertheless, the increased understanding of the interactions of energetic particles with the upper atmosphere provided by such observations has greatly increased their value. As interest in auroras increased, the early visual and photographic observations of their shapes and colours were supplemented with spectroscopic methods that provided more precise information on the characteristics of the upper atmosphere, using knowledge of the variation of colour with altitude and composition. These ground-based observations, however, did not allow for systematic observation of the entire auroral region around the Earth's poles.

56. It was only after the launch of the meteorological satellites of the United States Data Meteorological Satellite Program (DMSP) in the 1970s that the first ultraviolet observations of the auroral ovals from orbit were obtained. The first scientific satellite equipped with cameras designed to take pictures of the auroras in both visual and ultraviolet light, Dynamics Explorer 1, was launched by the United States in 1981. The Dynamics Explorer provided images of the auroras on both the day and the night sides of the Earth, and also recorded the geocorona, a huge region of the upper atmosphere where the atomic hydrogen scatters solar ultraviolet radiation. And in 1986 and 1987, simultaneous measurements of electric

and magnetic fields, particle distributions and plasma composition and waves as well as ultraviolet imaging of the aurora were carried out by the Swedish Viking satellite.

57. In addition to the auroras, there are a variety of other light emissions in the upper atmosphere, in both day and night skies, which are characteristic of particular atoms, molecules and ions. This "airglow" is of considerable interest, since it permits the study of atmospheric composition from the ground or from satellites over wider regions than the auroras. In the daytime, the strongest airglow phenomena arise by fluorescence, i.e., the absorption of solar energy followed by re-emission at longer wavelengths. Other airglow phenomena are generated by the recombination of ions with electrons, or of oxygen atoms with each other. These processes are visible mainly during the night and constitute the "night airglow", or "nightglow".

58. The brightest airglow emissions are due to oxygen ions in the lower F-region (150-200 km), where they recombine during the night producing a green spectral line (558 nanometres (nm)) and a pair of red lines (630 and 636 nm). Since these lines are also prominent in auroras, they are called the auroral green and red lines. Another green line is produced during regeneration of molecular oxygen from two oxygen atoms. During the daytime, a very intense band of infra-red lines (1,270 nm) is produced by the dissociation of ozone into molecular oxygen.

59. Ground-based observation of airglow is very difficult and often impossible in daylight. New ground observation techniques such as laser radar (lidar) are overcoming the obstacles and providing more detailed results on such phenomena as the strong seasonal variations in sodium in the upper atmosphere, the increased concentrations of lithium following thermonuclear explosions (prior to the test-ban treaty) and, more recently, the diffusion of lithium or barium after experimental release from satellites. The source of these metals, including sodium and potassium, in the upper atmosphere is thought to be the vaporization of meteors.

60. Aurora and airglow observations from space use special cameras or photometers that can record very faint emissions while protecting the detectors from the overly intense light. The sensors include both fully automatic devices and instruments serviced by astronauts.

61. An unexpected luminiscence, called the "Shuttle glow", was first noticed during the Space Shuttle flight STS-3 in 1982. The front surface of the vehicle was covered with a glowing orange layer visible to the naked eye on the night side of the orbit. It was subsequently photographed on other Shuttle missions and noted on other spacecraft in low Earth orbit. The glowing region is above the spacecraft surface and usually is 5 to 10 cm thick. The Shuttle glow is believed to be generated by the spacecraft catalytically, particularly through reactions of oxygen. It is not present on surfaces which are shielded from the oncoming atmospheric particles. Experiments in which various materials were exposed on the Shuttle's Remote Manipulator System revealed a different glow for each material.

62. The discovery of the spacecraft glow is a timely reminder of the fact that satellites in low Earth orbit - but not only there - are not free of the influence

of the surrounding environment, a fact that must be taken into account in designing scientific experiments. Otherwise, measurements of natural radiances can be contaminated by this induced radiation.

F. Active plasma experiments in space

63. Experimental chemical releases into the upper atmosphere, particularly of sodium, barium, strontium and lithium, have been conducted for several decades to study winds in the mesosphere and thermosphere and electric fields in the ionosphere and magnetosphere. World wide, the total number of experimental gas releases has been less than 400, and the total mass of the released material has been about 5 tons. Most of the individual releases have been in the range of 10 to 50 kg, and a few have exceeded 100 kg. Once released and exposed to short-wave solar radiation, ionized particles of these metals can be easily tracked by optical or radio methods. The experiments create glowing clouds which are transient in nature, usually lasting some tens of minutes and in some cases up to an hour or two. The evolution of the chemical cloud is determined by diffusion, gravitational settling and winds, as well as by electric and magnetic field influences for ionized constituents.

64. While the early experiments used sounding rockets to release the clouds, the availability of satellites has made it possible to conduct "active experiments in space". The kinetic energy of 100 kg of material at an orbital velocity of 8 km/s is sufficient to significantly modify and disturb, temporarily, the natural upper atmosphere environment, as well as to simulate natural phenomena, for example by the creation of "artificial comets". In 1984 and 1985, several large releases were conducted by the Active Magnetospheric Particle Tracer Explorer (AMPTE) programme, a joint venture of the United States, the Federal Republic of Germany* and the United Kingdom of Great Britain and Northern Ireland. The primary objective of the mission was the release of tracer elements of lithium and barium into the solar wind, the magnetosheath (the transitional area between the solar wind and the magnetosphere) and the magnetotail.

65. Another dedicated spacecraft, the Combined Release and Radiation Effects Satellite (CRRES), was launched in July 1990. It was injected into an elliptical orbit 330 km to 33,600 km above the Earth and contained 16 canisters of barium, 6 of lithium, and 1 each of strontium and calcium. This highly elliptical orbit allowed controlled releases at specific altitudes - at perigee, at apogee and at mid-altitudes of 1,000 to 3,000 km. The releases at lower altitudes allowed observations of the interaction of plasmas with magnetic fields, interaction of neutral and ionized constituents of the upper atmosphere, the structure and chemistry of the ionosphere and the structure of electric fields. The

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* Through accession of the German Democratic Republic to the Federal Republic of Germany with effect from 3 October 1990, the two German States have united to form one sovereign State. As from the date of unification, the Federal Republic of Germany acts in the United Nations under the designation of "Germany".

high-altitude releases were designed to study the interaction between the magnetosphere and the ionosphere and the effects of artificial plasma injections upon the stability of trapped particles in the radiation belts.

66. Observations of released particles are made with an extensive network of ground-based optical instruments and portable very-high-frequency (VHF) radar stations. The ground observations are usually complemented by observations from instrumented research aircraft. The satellites that release the materials also carry sensors to monitor the plasma and the state of the magnetic fields at the orbital altitudes.

67. Several ionospheric and magnetospheric research experiments using satellites are currently in progress or in preparation, including AKTIVNYI, APEX and INTERBALL by Intercosmos, and CLUSTER by the European Space Agency (ESA). Some of them include injections of gases, energetic particles or electromagnetic waves into space and observation of the effects by several satellites in complementary orbits.

III. EXTERNAL FORCES ACTING ON THE UPPER ATMOSPHERE

A. Solar radiation into the upper atmosphere

68. The intensity of solar energy at the top of the Earth's atmosphere is called the "solar constant", with a value of roughly 1,370 W/m^2. In the past, solar radiation was measured from high-altitude observatories, balloons, aircraft or rockets, and the solar constant was calculated by correcting for atmospheric absorption. The uncertainties due to atmospheric absorption and the calibration of the sensors were such as to preclude reliable measurements of small variations. Recently, direct satellite measurements of solar radiation have become sufficiently accurate to give the first clear evidence of short-term variations of the "solar constant", variations of a few tenths of a per cent. Longer-term variability is more difficult to establish, mainly due to the difficulty of calibrating instruments on different satellites over a long time span. While the effects of such small changes in solar output are not understood, they may cause significant meteorological and climatological effects, which could in turn have substantial effects on the biosphere and human activities.

69. The solar spectrum, especially in the visible and infra-red regions, corresponds roughly to the energy distribution of an ideal "black body" at a temperature of about 5,800° K, with some irregularities due to absorption in the solar atmosphere. About 99 per cent of the energy in solar radiation lies in the spectral interval from 250 to 4,500 nm and has a maximum in the visible region around 480 nm. About 40 per cent of the energy is received in the visible region (400 to 700 nm) and only 10 per cent at wavelengths shorter than the visible.

70. Large short-term fluctuations in X-ray and extreme ultraviolet (EUV) radiation have been frequently observed, correlated with solar flares and sunspots. In the case of very large solar flares, high-energy particles can penetrate down to the Earth's surface. Similar fluctuations are known to occur in solar microwave emissions at 10.7 cm, but since the microwave part of the solar spectrum carries

very little energy these fluctuations serve only as indicators of solar activity at higher energies. In the longer term, solar radiation, particularly at high energies, varies with the 11- and 22-year sunspot cycles. A case of solar variation on a very long time-scale is the "Maunder Minimum", the period between the years 1645 and 1715 which was characterized by a virtual absence of sunspots and is sometimes referred to as the "Little Ice Age". Another recently discovered variation in solar behaviour is manifested in oscillations in the size and shape of the Sun, a phenomenon now being studied in the new branch of solar physics known as helioseismology.

71. The incoming solar radiation at the top of the atmosphere at a given time and place depends not only upon solar output but also upon the Earth-Sun distance and the solar elevation angle at the surface. These two parameters depend in turn upon the latitude and the season as well as the characteristics of the Earth's orbit, including the eccentricity, the angle between the equator and the orbit (the obliquity) and the position of the perihelion. At the present time, the eccentricity of the Earth's orbit around the Sun is about 0.0167, giving a variation of incoming radiation of 3.3 per cent about its mean value, with a maximum in January (perihelion) and a minimum in July (aphelion). The orbital elements, however, are not constant but vary slowly, with periods of about 100,000 years for obliquity and 21,000 years for the perihelion position. The various changes in the orbital elements affect the seasonal distribution of incoming radiation. It now seems clear that these orbital cycles are related to the long-term climatological changes of the ice ages, but the mechanism by which these small natural changes in seasonal distribution can cause such major effects is not known. These effects are entirely independent of other climatological phenomena arising from human activities and their effect on the atmosphere.

72. Precise measurements of solar radiation above the Earth's atmosphere were initiated in 1978 by a special radiometer on the Nimbus-7 satellite. More advanced radiometers were subsequently launched on the Solar Maximum Mission (SMM) and the Earth Radiation Budget Satellite (ERBS). These radiometers are believed to have accuracies of better than 0.1 per cent. Despite some differences in their results, they were consistent in showing a decline in solar irradiance of about 0.1 per cent between 1979 and the mid-1980s, with a partial recovery by 1989.

73. Instruments on Nimbus-7 and the ERBS satellites are expected to continue making observations during the 1990s, but the SMM satellite re-entered the atmosphere in 1989. Together with new satellites, including the Upper Atmospheric Research Satellite to be launched in 1992, ongoing observations by existing satellites are very important for determining whether there is currently a long-term decline or a cyclical variation in solar radiation. To distinguish between the two possibilities, long-term measurements of solar radiation over at least two 11-year solar cycles would be necessary. It would also be valuable to measure simultaneously the oscillations in solar size and shape, which according to recent observations seem to follow a trend opposite to the variation of solar radiation.

B. Absorption of radiation in the upper atmosphere

74. The main factors that determine the overall climate of the Earth-atmosphere system are the input of solar radiation, the composition of the atmosphere and the Earth's surface characteristics. Solar radiation incident on the Earth and its atmosphere provides the ultimate driving force for all chemical and dynamic processes in our environment. On the other hand, the Earth radiates long-wave radiation into space, thereby cooling the planet. On a global and annual average, a net balance exists between solar heating and long-wave cooling. However, at any particular location and time, an imbalance can exist which acts as a driving force for the global circulation of the atmosphere.

75. A large portion of the incoming solar radiation is reflected back into space without entering into the thermal budget of the Earth-atmosphere system. The amount of radiation reflected divided by the total incoming radiation is called the "global albedo". For the entire planet, the global albedo is about 30 per cent. Clouds contribute about 25 per cent, and the atmosphere and surface contribute the remaining 5 per cent. The local albedo varies according to cloudiness and the distribution of the continents and oceans.

76. Part of the incoming solar radiation is absorbed into the atmosphere and converted directly into heat and does not reach the Earth's surface. Only a very small part of the absorbed energy results in chemical dissociation and ionization of molecules and atoms. In the upper region of the thermosphere, above about 100 km, solar radiation with wavelengths shorter than 180 nm is absorbed largely by molecular oxygen. It is that absorption of ultraviolet radiation that affects the temperature of the thermosphere and relates it to solar activity.

77. Solar radiation at longer wavelengths in the ultraviolet, between 180 and 290 nm, penetrates deeper into the mesosphere and stratosphere, to about 20 to 50 km, where it is absorbed by molecular oxygen and ozone. This part of the ultraviolet spectrum, however, shows very small fluctuations, and no variations in the temperature in the ozone layer due to such fluctuations have yet been observed.

78. Solar radiation that has not been absorbed into the higher layers, usually radiation of wavelengths longer than 290 nm, reaches the lower stratosphere and troposphere. This portion of the spectrum contains more than 97 per cent of the total incoming energy. On average, only about 18 to 20 per cent of the incoming energy is absorbed in the lower atmosphere and 45 per cent at the Earth's surface. The absorbed energy is re-emitted at infra-red wavelengths by both the atmosphere and the surface. Because most of the surface infra-red radiation is trapped by clouds and greenhouse gases, primarily water vapour and carbon dioxide, and subsequently re-emitted back to the ground, the surface is currently about 33° C warmer than it would be without this effect. This natural greenhouse effect is, therefore, a vital factor in the Earth's climate. Without it, the average surface temperature would be -18° C, instead of the present 15° C, and the Earth would be a frozen, lifeless planet.

79. In the lower stratosphere, the absorption of solar energy is fairly small, and there is a delicate balance between this absorption and the emitted long-wave radiation. As a result, the equilibrium between the absorption of solar energy and

the emission of infra-red radiation can be easily disturbed by the addition of new absorbing material such as volcanic dust.

C. Other inputs into the upper atmosphere

80. There are other inputs into the upper atmosphere in addition to electromagnetic radiation and atomic and subatomic particles. The natural dust particles and larger objects coming from outer space are called meteorites or micrometeorites. The influx of meteoritic material into the upper atmosphere is estimated at 2 to 6 x 10^6 kg/year, which is a far from negligible contribution to the atmospheric system. Some photometric studies during lunar eclipses and photometric observations from orbit seem to indicate the existence of a "high absorption layer" in the upper atmosphere, at an altitude of 80 to 100 km. This layer may be formed by particles of meteoritic material which are descending slowly following periods of high meteorite activity or "meteor showers".

81. Human space activity also introduces artificial material into the upper atmosphere. When a space object descends to about 110 km altitude, it heats up by friction with the atmosphere and is ultimately vaporized as it lowers into the denser atmosphere. Only large and dense parts can survive atmospheric re-entry and reach the surface. Human space activities thereby cause some pollution of the upper atmosphere. The total contribution of artificial objects to the material arriving from outer space is now estimated to be less than 10 per cent of the input of natural dust.

82. During the final re-entry of a spacecraft into the Earth's atmosphere, it usually breaks up into a trail of debris scattered over a fairly long, but narrow track. Because of the very high temperatures reached during re-entry, large quantities of metal vapours and oxides are produced and dispersed into the upper atmosphere. Such vapours can influence the balance of electrically charged particles and, locally at least, change the conditions in the ionosphere. At present, however, vaporized meteorites are the main source of metal in the upper atmosphere, and the human contribution is still very small. Metallic ions of meteoric origin are apparently responsible for the "sporadic E layers" in the ionosphere.

83. Experimental chemical releases for research in the upper atmosphere, with a total released mass of several tons, have shown no adverse effects on the terrestrial environment. The maximum total mass injected into the upper atmosphere in these experiments, with the exception of barium and lithium, is only a minute fraction of the input of meteoritic mass.

84. It is a popular belief that recently observed weather anomalies around the world are caused by "those satellites and rockets". But in spite of many hundreds of rocket launches since the beginning of the space age, no concrete evidence has been found to suggest that rocket effluents may be dangerous to our environment. The only observed effects have been instances of local ionospheric "holes", lasting for several hours, when rocket engines burned within the ionospheric F-region. The addition of carbon dioxide from 100 Shuttle launches per year would amount to only one part in 100,000 of the yearly injection rate from the burning of fossil fuels.

85. The release of chlorine into the stratosphere from the hydrogen chloride in Shuttle propellant amounts to less than 1 per cent of the industrial input from chlorofluorocarbons, while the generation of nitric oxide during re-entry amounts to about 0.1 per cent of the natural production rate. The Soviet launcher system Energiya, which uses cleaner-burning liquid boosters, is believed to have even less effect on the environment. However, new studies on local effects of rocket launches are in preparation, and clean-burning solid propellants for advanced launch systems are being tested in the United States.

IV. UPPER ATMOSPHERIC EFFECTS ON WEATHER AND CLIMATE

A. Correlation of solar activity with weather

86. Due to the complexity of processes in the lower levels of the atmosphere, it is very difficult to separate the individual meteorological or climatological effects of various factors. In recent years, however, some studies have shown a probable association between the 11-year solar cycle and atmospheric processes at all levels, from the surface to the top of the stratosphere. Two atmospheric phenomena have been the subject of particular attention: the major midwinter warmings in the polar stratosphere and the quasi-biennial oscillation (QBO) in the equatorial stratosphere. In some years, the normally cold Arctic stratosphere becomes warmer than the mid-latitude stratosphere for about a month. At the same time, the prevailing west winds are replaced by easterlies. The warmings are unique to the northern hemisphere and are associated with the amplification of planetary waves in the troposphere and the stratosphere. QBO is the change in wind direction between west and east in the equatorial stratosphere about every second year.

87. Observations of stratospheric warmings and QBO during the last three solar cycles have revealed significant correlations between them and solar activity, as indicated by solar radio emissions at 10.7 cm. It is not clear, however, how the small variations in solar input could produce such large atmospheric responses, but it appears that some triggering effect on this part of the atmosphere is involved.

B. The stratosphere and climatic change

88. There is a growing realization that the accumulation of carbon dioxide and other trace gases in the atmosphere may lead to a pronounced alteration of the Earth's climate due to an enhanced greenhouse effect. Molecules of these "greenhouse gases" absorb infra-red radiation and thus reduce the amount of terrestrial infra-red radiation that escapes to outer space. According to the models of the greenhouse effect, there should be a decrease in stratospheric temperature about an order of magnitude larger than the warming of the Earth's surface. Stratospheric temperature measurements, including satellite measurements, should therefore provide a sensitive indicator of climate change due to the greenhouse effect.

89. While carbon dioxide, which has increased by 25 per cent since 1740 and is currently increasing by 0.4 per cent per year, is generally regarded as the main cause of the increased warming of the planet, any gas which absorbs infra-red radiation contributes to the greenhouse effect. Because the existing concentration of carbon dioxide in the atmosphere already absorbs most of the radiation in its absorption band, absorption by other gases at different wavelengths makes a disproportionate addition to the overall effect. For this reason, an increased input of methane has 25 times the effect of adding the same number of molecules of carbon dioxide; freons have an effect 10,000 times as great.

90. COSPAR Sub-Commission A.2 has recommended the measurement of stratospheric temperature profiles together with vertical profiles of greenhouse gases and aerosols in the stratosphere. There is a great need for small dedicated research satellites for long-term measurements, supported by reliable ground observations. The inclusion of high-spectral-resolution instruments for observing the outgoing long-wave radiation on such future satellites was also recommended.

91. The highest priority, however, would appear to be satellite measurements of the global mean temperature at altitudes of 40 to 45 km, where most greenhouse models predict maximum cooling. The monitoring should be carried out both in summer, when the natural variability of the stratosphere is least, and in spring, when polar ozone holes tend to form.

92. However, since the natural variability of the stratosphere is not adequately understood, it is not yet possible to make any definitive statements about the relationships between observed temperature trends in the stratosphere and increases in greenhouse gases. Measurements of stratospheric temperatures and concentrations of trace gases and aerosols should therefore be used as inputs into greenhouse models to verify their validity and improve their accuracy. Only then can the models be used to predict when global warming induced by human activity will become observable.

C. Aerosols

93. After greenhouse gases, the second most important factor in changing the global climate is fine atmospheric dust particles and liquid droplets known as "aerosols". Stratospheric aerosols have a high degree of natural variability and have been better measured than tropospheric aerosols.

94. Stratospheric aerosols arise mainly from volcanic eruptions. Benjamin Franklin first noted that volcanic aerosols reflect sunlight to space, and that therefore the eruption of a large volcano in Iceland could have been responsible for unusual cold in 1783-1784. Many subsequent studies have revealed a tendency for eruptions that produce large amounts of aerosols over much of the Earth, such as Tambora (1815), Krakatoa (1883) and Agung (1963), to be associated with global cooling of a few tenths of a degree Celsius for a year or two after the eruption. However, since this is comparable to normal global temperature fluctuations, a cooling effect cannot be observed for every large volcano.

95. After the Agung eruption in 1963, there was a marked increase in stratospheric particle concentration. For about two years, sunsets were noticeably more brilliant, reminiscent of the well-known post-Krakatoa atmospheric effects. A decrease in direct solar radiation following several major recent eruptions has been recorded, ranging from 5 to 20 per cent. The reduction in radiation reaching the ground has been much less than the reduction in direct radiation; the Agung stratospheric particles probably reduced the solar radiation at the surface by less than 1 per cent.

96. In situ stratospheric measurements during the past few decades, after such eruptions as those of Mt. St. Helens (1980), El Chichón (1982) and El Niño (1982-1983), show that the dominant volcanic aerosols are small droplets of sulphuric acid which form from volcanic sulphur dioxide and persist a year or more after the eruption. Assuming that the aerosols of earlier volcanoes were also sulphuric acid, estimates of atmospheric transparency can be used to calculate the volcanic aerosol climate effect. The uncertainty in the resulting 10-year-mean aerosol effect is probably less than a factor of 2.

97. The calculated volcanic effect on climate at times rivals or even exceeds the greenhouse effect, but the latter clearly dominates the long-term trend. Moreover, the volcanic effect is irregular, and therefore a clustering of several volcanic eruptions is required for a significant long-term impact on climate. Nevertheless, it is clear that stratospheric aerosols need to be monitored in order to determine the causes and effects of climate change during the next few decades.

98. As stated in the latest international scientific assessment of stratospheric ozone, the global quantity of stratospheric aerosals, which peaked after the eruption of El Chichón in 1982, has now generally declined. Although low in 1989, stratospheric aerosols have not yet reached the lowest levels observed in 1978-1979. The 1989 levels should have little or no effect on ozone measurements.

99. Stratospheric aerosols affect not only surface weather conditions but also the stratospheric ozone layer. In the case of the Antarctic polar stratospheric cloud, aerosols have been shown to promote ozone destruction through complex chemical reactions. In addition, laboratory studies suggest that ozone destruction may occur on the surface of aerosols composed of ice and sulphuric acid, which are greatly enhanced after volcanic eruptions. Those aerosol surface reactions could be an important mechanism for ozone destruction on a global scale. Aerosols can also distort ozone measurements made by remote sensing instruments and hence need to be taken into account in ozone monitoring.

100. In the 1970s, there was speculation that increasing concentrations of man-made aerosols might cause a "small ice age". This speculation was supported by the observation that the average temperature in the northern hemisphere had declined slightly between 1940 and 1970. Industrialization, urban pollution, mechanized agriculture and population pressure in semi-arid lands had added noticeably to the tropospheric aerosol content. Although in certain circumstances, such as the absorbing haze in the Arctic, anthropogenic aerosols can have a warming effect, the overall direct radiative impact of man-made aerosols is clearly one of cooling. In the past decade, with the recognition that the global temperature was again rising,

tropospheric aerosols have received less attention than the greenhouse effect, but they have not been disproved as an important agent of climate change. Tropospheric aerosols can also be transported by turbulence to higher levels of the atmosphere and influence conditions there.

D. Ozone depletion

101. While ozone is a very minor constituent of the stratosphere, with a maximum concentration of less than 10 parts per million, it is sufficient to stop most of the life-threatening ultraviolet radiation from reaching the Earth's surface. In 1974, however, a possible long-term decline in stratospheric ozone concentrations was reported, and it was suggested that man-made chemicals might be responsible for that effect. This trend has been subsequently confirmed, and direct links between ozone destruction and chlorofluorocarbons (CFCs) have been firmly established. These industrial gases, used mainly as coolants in air-conditioners and refrigerators, are very stable at lower atmospheric levels. But when atmospheric turbulence transports them into the stratosphere, solar ultraviolet radiation breaks the molecules apart, releasing chlorine, each atom of which can destroy about 100,000 ozone molecules. In addition to ozone, there are other gases, such as bromides and oxides of nitrogen, which can affect ozone destruction.

102. The importance of ozone destruction was confirmed in 1985 by the discovery of a seasonal "ozone hole" above Antarctica. Since 1985, detailed measurements from the ground, from instrumented aircraft and from satellites have shown that the hole recurs every year and has tended to increase in magnitude. The hole usually reaches its maximum extent in September, at the end of the southern polar night, when the concentration of ozone falls to as low as 50 per cent of its normal value.

103. It is believed that ozone is broken down in complex chemical reactions inside the thin polar stratospheric clouds, which are shown by satellite observations to occur most frequently over Antarctica. Indeed, the abundance of reactive chlorine and bromine compounds in the Antarctic stratosphere in the southern springtime is elevated 50 to 100 times over normal stratospheric levels, an increase which is sufficient to explain most of the rapid ozone loss observed each year following the return of sunlight to Antarctica. In situ and satellite measurements indicate that nitric acid vapour is a key element in the formation of polar stratospheric clouds, and that denitrification of the stratosphere is therefore an indicator of the potential for ozone depletion. However, the exact process of cloud formation is not yet fully understood.

104. Year-to-year variations in the extent of the ozone hole appear to be related, in part, to the quasi-biennial oscillation (QBO), the periodic reversal of the equatorial stratospheric winds. In 1987, the Antarctic ozone hole was particularly strong, but there was substantially less ozone reduction in 1988, possibly due to the observed temperature extremes between the two years, which affected the abundance of stratospheric clouds. Tropospheric weather systems can also influence stratospheric temperatures and water vapour abundance on a regional scale, and this would in turn influence stratospheric cloud abundance and ozone changes.

105. It was recently found that the same ozone-destroying processes take place in the Arctic stratosphere as well. Preliminary analysis of measurements made in the spring of 1989 have confirmed the existence of polar vortex and ice clouds over the Arctic and revealed an observable ozone depletion of 15 to 17 per cent at some altitudes. Chemical analyses showed increased levels of active chlorine and lower-than-expected levels of nitrogen oxides in the Arctic stratosphere. However, in contrast to Antarctica, the warming of the Arctic polar vortex generally occurs prior to the arrival of sunlight, making conditions less favourable for ozone destruction. The degree of Arctic ozone depletion will likely depend on the particular meteorology of each Arctic winter as well as atmospheric levels of chlorine and bromine.

106. Satellite measurements of ozone are provided by meteorological satellites, such as Nimbus-7 and NOAA-9 and 11, which carry the total ozone mapping spectrometer (TOMS) and solar and backscattered ultraviolet (SBUV) spectrometer. In addition to providing global coverage, these observations have proved useful for verifying the consistency of ground-based instruments in order to identify erroneous readings and remove the effects of long-term drift in instrument calibration.

107. The SBUV spectrometer is also being used for short-term measurements on some Space Shuttle flights, beginning with STS-41 in 1990, and the TOMS instrument is to be carried on the USSR Meteor-3 spacecraft in 1991 and on the Japanese Advanced Earth Observation Satellite (ADEOS) in 1995.

108. For studying changes in the vertical distribution of stratospheric ozone, the only satellite observations available are from the Stratospheric Aerosol and Gas Experiment (SAGE), carried on the second Applications Explorer Mission (AEM-2) satellite from 1979 to 1981, and on the Earth Radiation Budget Satellite (ERBS) from 1984 to 1988.

109. Ground-based measurements indicate a reduction in ozone of 3 to 5 per cent between 1969 and 1988 during northern hemisphere winters, after allowing for seasonal variations, the effect of QBO and the 11-year solar cycle. This is the first analysis that has shown a statistically significant downward trend. Existing ground-based data are inadequate to determine changes over tropical or southern regions. While satellite data can provide the desired global coverage, existing satellite data are too limited to allow differentiation of natural and human-influenced variations in ozone abundance. As more satellite data are collected, the satellite and ground-based observations will serve as valuable complementary sources of information on global trends in ozone concentration.

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